CHAPTER 11

Renewables Have Won

What a man believes on grossly insufficient evidence is an index into his desires – desires of which he himself is often unconscious.

Bertrand Russell

Recently, I had a three-way conversation with a leading environmentalist and a cabinet minister. For me, it was *déjà vu*. Almost 20 years ago I had the same conversation with a different leading environmentalist and a different cabinet minister.

Politician: "At the next cabinet meeting we'll be discussing policies to advance clean energy. This is a rare opportunity and I don't want to mess up. What arguments should I make for a stronger renewable energy policy?"

Environmentalist: "Point out that renewables are already cheaper than fossil fuels and attracting more investment, so pushing renewables has no cost for the economy."

Me: "Did you say renewables are cheaper than fossil fuels? If true, why should government do anything? If renewables have won the economic competition, then government can take credit for falling GHG emissions without lifting a finger."

Politician (with a smile): "Exactly my thoughts as I heard that."

Environmentalist: "Well, it's true. Renewables are the cheapest option. But subsidies to fossil fuels are unfair. If we get rid of these, we'll accelerate the transition to zero-emission energy. Argue this to cabinet."

Me: "Good luck. I don't think you'll get far trying to eliminate subsidies. They're difficult to determine, and many economists dispute what some people call subsidies. But I guarantee that the cabinet will fix on your argument that renewables have won. This justifies its delay of politically difficult decarbonization policies. If you want renewables to rapidly replace fossil fuels, you need cabinet to implement more stringent pricing or regulatory policies, and you need them to do that now."

The conversation dragged on, but you get the point. Statements by renewables advocates and environmentalists that renewables are now cheaper than fossil fuels sound encouraging. But if they let politicians off the hook from enacting stringent climate policy, then they inadvertently slow the energy transformation. We can't afford that.

Stories about the economic victory of renewables are decades old. With hindsight, we know with certainty that the earlier claims, like the one I encountered 20 years ago, were overly optimistic. Today, some renewables are much cheaper, with falling costs and a promising growth rate. But often that growth is because of compulsory government policies that require a growing market share for renewable electricity (the renewable portfolio standard), provide a subsidy (feed-in tariffs and tax credits), or require minimum blending of ethanol and biodiesel into conventional gasoline and diesel (biofuel mandates). If we inadvertently convince politicians they don't need strong policies to reduce the burning of fossil fuels, we contribute to the continued failure against the climate threat. Politicians need a push because, as I explained in Chapter 6, all effective climate policy is politically difficult.

For an academic, I have had my share of experiences in the policy-making arena, including the occasional direct window into cabinet decision-making. Cabinet members (or secretaries in the US) are like most of us – sincere, wanting to do right. But to survive in the rough and tumble world of politics, they must have sensitive antennae for anticipating and avoiding policy decisions that cause a strong negative reaction from some quarters. When such opposition appears, or can be foreseen, the cabinet conversations are intense, but decisions may be evasive.

One raconteur of cabinet decision-making is Pat Carney, Canada's former energy minister in the 1980s Conservative government. Between my undergrad degree and the start of my masters, I worked for the small economic consulting firm she ran before entering politics. We became friends. Years later, when I was a professor and she no longer in parliament, although still an appointed member of Canada's Senate, she gave annual guest seminars in my graduate energy course. To the students' bewilderment, her only required advance reading was a chapter from the book version of the British TV sitcom, *Yes Minister*.[1] In one memorable passage, the deputy minister explains to the inexperienced junior advisor how to discourage their cabinet minister from pursuing a particular policy. What they should say is, "Bravo Minister. You are *very* courageous to pursue that policy." Then wait a few days.

The policies that are essential to transform our energy system are not politically easy. They require leadership. Politicians who sincerely want to contribute need to be told this inconvenient truth, and guided to policies that have a lower political cost per ton reduced, as I described in Chapter 6. Otherwise, they will delay, waiting for renewables to outcompete fossil fuels.

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I am frequently asked by non-experts why they never hear about how to transform our energy system to prevent climate change. People are shocked at my response: energy analysts have publicly reported on this transformation with great fanfare since the 1980s. Of course, in the daily deluge of news, why would they remember this particular topic?

It was the so-called oil crisis of the 1970s that launched the field of 'energy system transformation.' The first major studies explored how humanity might wean itself from fossil fuels, given the widespread concern about imminent oil scarcity. At the time, several major institutions touted nuclear power as the obvious replacement for diminishing fossil fuels. But an alternative, renewables-focused future was sketched by some researchers, notably Amory Lovins of energy efficiency fame, as I explained in the previous chapter.

In Chapter 3 I noted that the highest-profile studies into transforming the global energy system are the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), with its five comprehensive assessments since 1990.[2] In these reports, energy-modeling teams explore multiple paths for achieving dramatic GHG emissions reductions over several decades. Each path has a different contribution from the major GHG-reducing options: energy efficiency, nuclear power, renewables, land-use change, and carbon capture and storage when using fossil fuels or extracting CO_2 directly from the air. When these multiple paths are combined with a range of assumptions on population and economic growth, global income equity, and key technological uncertainties, the graphed results looked like a downward sloping mass of intertwined spaghetti.

These studies produce a consistent takeaway message. First, we need several decades to fully transform the energy system for significant GHG reductions. Second, this can occur without major technological innovations, although cost-reducing innovations will continue as commercialized technologies increase market share. Third, the cost is manageable if we prioritize the lowest cost options and transform the energy system at a pace that reflects the replacement rate of electricity plants, industrial plants, vehicles, and buildings. This is the consensus view from assessments prepared by experts crafting a compromise summary of the leading evidence. Outside of these collaborative assessments, there are of course some disagreements among individual researchers.

The prolific energy writer Vaclav Smil is known for emphasizing the inertia of energy systems, hence the long time required for system transformation. In the 2017 edition of his book, *Energy Transitions*, he takes aim at researchers and studies that in his view are too optimistic about the possible rate of change.[3] He argues that changing an energy system depends on multiple interrelated developments, each with its own countervailing inertia. A wholesale switch to electric cars requires more than just innovating long-lived batteries and convincing people to buy this unfamiliar device, which in itself takes time. It also requires growth of zero-emission electricity generation to power the cars, installation of a network of domestic and public rechargers, reinforcement of the electricity grid and building electrical systems to handle the higher load, and development of widespread expertise in electric vehicle maintenance and repair.

Smil and most other system researchers note that the feasibility and cost of energy system transformation is lower if we are open to the widest possible set of GHG-reducing options. Examples of major studies supporting this claim are the 2012 *Global Energy Assessment*, in which I participated, and the 2015 *Deep Decarbonization Pathways Project*.[4]

People who believe renewable energy is the only decarbonization option worth pursuing (alongside energy efficiency of course) follow the research of Mark Jacobson of Stanford University. In recent studies, he argues that humanity can switch quickly and completely to a sub-set of our renewable energy options without any effect on GDP.[5] He claims that a transition to 100% renewables will not increase the cost of electricity, home heating, industrial production, and mobility of people and goods. Moreover, he claims that this can be achieved while meeting the rapidly growing demand for energy services by people in the developing world. And, all of this while restricting the renewables options to wind, water, and solar – the 'WWS path.'

In support of this scenario, Jacobson highlights the dramatic decreases in the cost of electricity from wind and solar. Figure 11.1 shows that the average price of electricity from wind in the US fell from 6 cents per kilowatt-hour in 2010 to 2 cents in 2017, while photovoltaic electricity fell from 14 cents to 4 cents. This is a truly remarkable development, especially considering all of the speeches I've heard over the years from entrenched fossil fuel defenders, who confidently predicted that the cost of renewables would never decline.

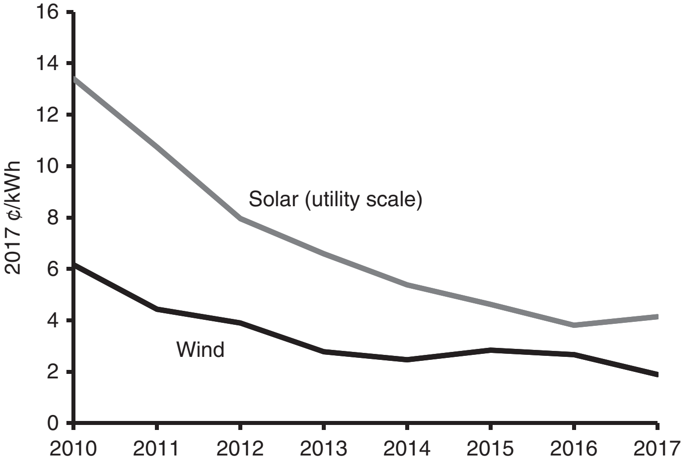

Figure 11.1 US solar and wind prices

Jacobson's water, wind, and solar scenario deserves serious consideration. But, as with the earlier work of Lovins, his findings have provoked significant criticisms from other researchers who argue that his limited reliance on wind, water, and solar will be much costlier than he claims.[6] Several experts went so far as to publish a 2017 paper in the Proceedings of the National Academy of Sciences which directly critiqued Jacobson's analysis.[7] He responded with a defamation lawsuit against the publisher and authors. But he later dropped it.

To an economist like me, the idea that it will be costlier if we exclude some low-emission options from competing to replace the burning of fossil fuels seems obvious. A decade ago, in *Sustainable Fossil Fuels,* I explored a decarbonization scenario in which renewables gradually came to dominate the global energy system, but some jurisdictions still retained a modest role for nuclear power and others relied on some carbon capture and storage to continue benefiting from their endowment of high-quality fossil fuels.[8] (This is why we must distinguish the high-emission burning of fossil fuels from the near-zero-emission use of fossil fuels when integrated with carbon capture and storage.) If the goal is decarbonization, why spend more than necessary, especially when the developing world can use any money it saves for welfare-improving schools, hospitals, housing, and infrastructure?

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When we look more closely at the "renewables have won" claim, perhaps it is no accident that Lovins is a physicist and Jacobson an engineer. Researchers can agree with them that it is physically and technologically feasible for the global energy system to become 100% renewable. But to most economists, their cost estimates for quickly achieving that 100% renewable future seem tainted by wishful thinking bias. They also seem to downplay the social challenges to fully transforming a global energy system that is currently dominated 80% by fossil fuels, and in which most energy demand growth is occurring in the developing world, as more of the planet's poorer people gain access to electricity and modern fuels produced primarily from fossil fuels.

When we shift from the technological feasibility perspective to economic feasibility, four factors challenge the "renewables have won" paradigm. The first is energy quality. (Physicists have specific terms like 'energy density' and 'power density.') When it comes to energy quality, fossil fuels are amazing. A half cup of gasoline has enough energy to lift a car to the top of the Eiffel Tower. Most renewables, as found in their natural state, don't have nearly that punch. Solar energy reaches the earth at a low power density, measured in watts per square meter. If that energy is converted into electricity using photovoltaic panels, a lot of land and equipment is required. To produce the same amount of electricity as a 1,000 megawatt coal or natural gas plant, a solar facility in a sunny location would require 100 times more land. There is room for reducing the land cost by covering rooftops with solar panels wherever possible. But the amount of investment per unit of energy provided is still usually greater for the solar option because of its lower energy quality.

Growing wood, straw, and grains to produce ethanol, biodiesel, biomethane, and perhaps bio-jet fuel also requires a lot of land. This leads to concerns that an effort to dramatically increase biofuels requires land that could otherwise grow food crops or sustain biodiversity in forests and grasslands. Researchers like Jacobson are aware of this problem, which is why his renewables scenario focuses on wind, water, and solar. But this means excluding the potential, as demonstrated in Brazil, to produce ethanol from sugar cane as a relatively low-cost substitute for gasoline.[9] While we should not rely on biofuels for wholesale replacement of gasoline and diesel, the use of forestry, agricultural and urban bio-wastes, and some marginal lands to produce an array of biofuels offers low-cost opportunities without major impacts.[10]

Wind, like solar, has a low power density. A lot of land must be covered with wind turbines to produce a significant quantity of electricity. Fortunately, the extra land needed for wind parks can usually be shared with other users, such as cattle grazers and grain growers. To avoid land-use conflicts, large-scale wind parks are increasingly located offshore. But throughout the world there is still an enormous amount of land available for wind turbines.

The second important factor when assessing the cost of scaling up renewables for electricity generation is 'capacity utilization.' (Electrical engineers refer to 'capacity factor.') This is the annual output of a facility compared to the output it could produce if running at full capacity every hour of the year. A coal or natural gas power plant can operate at full output almost all year, shutting down perhaps 5% of the time for maintenance – a 95% capacity utilization rate. In contrast, solar panels don't produce electricity at night. And because sunshine is less direct near dawn and dusk, solar power's optimal capacity utilization doesn't exceed 30–40%, and that only in the sunniest locations.

Wind also has a capacity utilization challenge, in this case because the wind is not always blowing at an optimal speed, and sometimes not at all. Nonetheless, I note that critics who decades ago argued (as I remember clearly) that a wind turbine's capacity utilization could never surpass 25% have been proven wrong. Today, with new turbine designs, the most favorable sites can reach 50%.

Conventional medium- and large-scale hydropower has reservoirs that in many regions can hold enough water to achieve 60% capacity utilization on an annual basis. But constructing more of these plants would entail major environmental impacts, which limits their potential role in a water, wind, and solar future. Smaller hydropower (run-of-river, micro-hydro, pico-hydro), because it lacks substantial reservoirs, is more acceptable. But since such facilities rely on natural stream flows, which in most locations vary seasonally, their capacity utilization rates are usually much lower.

The lower capacity utilization rates of these key renewable electricity sources means that much more capacity must be installed to generate a given amount of electricity. Vaclav Smil has shown that replacing 100,000 megawatts of fossil fuel generating capacity requires 150,000 to 300,000 megawatts of renewable capacity, depending on the mix of renewable sources. When we consider replacing all existing fossil fuel capacity with renewables, plus constructing all the new generating capacity for the growing electricity needs in the developing world, plus constructing all the new capacity needed for electrification of transport, industry, and buildings, the investment and construction per decade is astronomical. And this massive financial outlay is just to generate the extra electricity, before adding the additional financial resources involved in electrifying almost all energy end-uses in industry, transport, and buildings.

The third key factor in estimating the cost of increased renewables is that wind, solar, and small hydro, often the lowest cost renewables, are 'intermittent.' (Electricity operators use the term 'non-dispatchable.')

Electricity generation and consumption must be instantaneously balanced at all times and all places on the grid to avoid brown-outs and black-outs. Natural gas and coal plants are fully dispatchable, meaning that they can produce electricity at full capacity when it is needed and therefore most valuable. For some renewables this can also be true – wood-burning plants, geothermal plants, and large hydropower plants with reservoirs. But solar, wind, and small hydro can only produce electricity when nature cooperates – the sun shines, the wind blows, and precipitation and melting snow cause water to flow. For these non-dispatchable sources to dominate the energy system, they must be integrated with energy storage of some kind. This investment should be considered part of their cost, but when making comparisons with conventional electricity plants, advocates of these forms of energy often forget to include the full costs of storage.

They make this error when they compare electricity-generating options by a single metric – cents per kilowatt-hour (c/kwh). The figure above showed how much the costs of solar and wind have fallen when measured in cents per kilowatt-hour. This is great news. But it is a mistake to compare these costs of non-dispatchable electricity with the costs of electricity from dispatchable sources, and then conclude on this basis that these renewables are economically superior to dispatchable sources like fossil fuels and nuclear.

This is tantamount to comparing the costs of a dispatchable and a non-dispatchable ambulance service. The first is continuously staffed with paramedics. It can respond immediately to all emergency calls. The second has the same number of paramedics, but their work is unscheduled. Sometimes no one is available to respond to an emergency call. This non-dispatchable ambulance service has lower annual costs because the paramedics, being unscheduled, demand less pay since they can come and go as they please. But this non-dispatchable service saves far fewer lives. To focus only on the cost side of the ledger would rightly be seen as lunacy by the people reliant on this emergency service.

To make a valid economic comparison, whether with ambulance service or electricity service, we need to compare the value provided by each option next to its costs. In a 2012 article Paul Joskow compares the full costs and benefits of dispatchable and non-dispatchable electricity sources.[11] He uses the price of electricity in wholesale and retail trading markets to indicate its value at a given time. Like other leading analysts, he finds that dispatchable electricity sources can sometimes be 10 times more valuable than non-dispatchable sources. It depends on how the demand profile in a given jurisdiction (the configuration of peak and off-peak hours) correlates with the production profile of a given non-dispatchable renewable source, and on the relative shares of dispatchable and non-dispatchable sources. In brief, we cannot conclude that wind, water, and solar are economically superior to fossil fuels for generating electricity based solely on their relative costs per kilowatt-hour. Our comparison must include the value of their production or the cost of adding backup storage so that their output is dispatchable.

When we do include storage costs with wind and solar, the cost per kilowatt-hour is higher. In addition to batteries, energy can be stored as natural gas (to provide reliable backup from a gas-fired turbine), as compressed air, or as solid biomass, biomethane, or hydrogen. This storage adds to the cost per kilowatt-hour, but in most jurisdictions, electricity prices will increase less than 1% per year over the next two decades as GHG emissions fall, thanks to a rapidly growing output from renewables.

The fourth important factor when assessing the cost of scaling up renewables is to recognize that the prices of resources like fossil fuels are subject to feedback effects. (Economists refer to ‘market dynamics’ or ‘general equilibrium responses.’) I notice that renewables advocates often assume that fossil fuel prices will stay the same or rise, but won’t fall. This makes it plausible for them to *predict* the year when the falling cost of renewables, as depicted in Figure 11.1, descends below the costs of using fossil fuels, and hence the time when renewables win.

But as I explained in Chapters 5, 6, and 7, an understanding of how markets work leads to a different assumption. Like the prices of other commodities, fossil fuel prices rise and fall depending on the interplay of supply and demand, the appearance of cost-changing innovations and discoveries, and shifting consumer and firm preferences. When most people thought we were soon running out of fossil fuels, there was upward pressure on their price. When most people acknowledged that fossil fuels are plentiful, and innovations were lowering their production cost, there was downward pressure on price. At one time, markets were predicting rising coal prices. Today, markets recognize that coal prices will trend downward over the long term. Natural gas prices are historically low and unlikely to rise in the coming decades. Because of the shale gas innovations, there is still a huge amount of gas available at moderate to low costs. And these historically low prices are more likely to fall if humanity reduces its reliance on coal and to a lesser extent natural gas.

While the price of oil has some uncertainty today, when our GHG efforts are mostly ineffective, the price will trend downward if humanity gets serious about reducing GHG emissions. When the global transport industry is shifting away from gasoline and diesel toward electricity, hydrogen, ethanol, and biodiesel, the price of oil will be falling. When demand declines for a product, its price falls as high-cost producers are eliminated. It is easy to imagine the price of oil falling below $20 per barrel when humanity is seriously reducing GHG emissions. But at that low oil price, we won't be seriously reducing GHG emissions without high carbon prices or high stringency regulations. Renewables won't win without these.

These market dynamics should be accounted for by those calculating the costs of switching to renewables. Their analysis should show the prices of coal, oil, and natural gas falling in response to falling demand. Yet, I have not seen this in studies by those who claim that a transition to 100% renewables has little or no cost. Because of these normal market dynamics, the image that fossil fuels will soon be defeated by renewables should be replaced by the slap-stick comedy routine of a clown trying to pick up a ball – accidentally kicking it ahead each time she stoops to grab it. Small progress by renewables in taking market share from fossil fuels leads to lower fossil fuel prices, which frustrates efforts to take more market share.

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While I agree with the criticisms leveled at Lovins, Jacobson, and other renewables advocates that their economic analysis may be biased, I part company with those who argue the analysis is flawed simply because humanity is not following the path they present. For example, I have read works of Smil in which he refers to past visionary studies as long-term energy forecasts, which failed because they got it wrong.[12]

To me, this is to confuse scenarios with forecasts. A forecaster says, "This is my prediction for how the energy system is likely to unfold, given my judgment on the key determining factors." A scenario analyst says, "This is my scenario for how the energy system *could* be transformed, if society takes the necessary actions. This is not a prediction of what will happen, but rather a roadmap for what is feasible *if* society makes the necessary effort."

This distinction is important because past societies have rarely been interested in deliberately transforming their energy systems, and never on a planetary scale. We transitioned from the wood age to the fossil fuel age not by deliberate collective effort, but rather from the self-interested decisions of agents at all levels in society in response to discoveries, inventions, and shifting preferences. As societies industrialized, industries switched from burning wood to using coal-fired steam, then diesel engines, then electric motors because each option was superior to its predecessor. People switched from horses to trains, then cars, then planes for mobility, and from wood to fuel oil, then natural gas and electricity for heating buildings. There was no collective intentionality driving these transitions. The new options performed better. Governments neither selected technologies nor restricted environmental impacts, focusing instead on providing the legal and regulatory framework, financial backing, and infrastructure to help powerful economic interests develop these advantageous and profitable new technologies and processes.

Scenarios of what is feasible can play an important role in helping societies change direction. And in today's Anthropocene epoch, in which human actions have global impacts, it is important to develop global scenarios of alternative feasible paths. Certainly, it is important to critique such scenarios if we believe they are unfeasible for technical, economic, social, or political reasons, as Smil often does so convincingly. But I have never heard developers of future energy scenarios claim to be making a prediction. Criticizing their scenarios because society didn't follow the path they provided seems unfair and misleading.

Perhaps I am sensitive to this issue because it parallels some of the criticisms of my 2005 book *Sustainable Fossil Fuels.* In the book, I was careful to explain at length that I was combining prescription and prediction. My *prescription* was that, based on the science and economics, humanity should quickly reduce GHG emissions. This was a normative statement about what humanity *ought* to be doing. My *prediction* was that if society quickly reduced GHGs, carbon capture and storage would be important in regions endowed with quality fossil fuel resources.

In spite of this explanation, a few readers later argued that my "prediction" was incorrect because no region was fully committing to carbon capture and storage. But, as I explained, my prediction was contingent on society following the prescription that we rapidly reduce GHG emissions. I was not forecasting that humans would do this. If anything, I devoted the policy section of the book to explaining why acting on the climate risk is so difficult (as I also explain in Chapters 4, 5, and 6 of this book). To say I was wrong because so little carbon capture and storage happened in the last decade is to confuse my prescription with my prediction. There has not yet been a serious global effort to reduce GHG emissions.

In any case, we should focus on the technical and economic feasibility, and ultimately the social and political feasibility, of the alternative deep decarbonization scenarios. Whether we are talking about the wind, water, and solar scenario of Jacobson or the all-hands-on-deck scenario of other deep decarbonization studies, the issue of technical and economic feasibility is associated with the issue of innovation. How much innovation is required and how does it happen?

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In a TED talk a few years ago, Bill Gates explained why the planet needs a 'technology miracle' to avoid a climate disaster.

> If you gave me only one wish for the next 50 years – I could pick the president, I could pick a new vaccine, or I could pick a technology miracle that provides energy with no CO_2 emissions at half the cost of fossil fuels – this is what I would pick. This is the wish that would have the greatest impact. If we don't get this wish, the lives of the two billion poorest on the planet will be far worse . . . When I say a miracle, I don't mean something

> impossible. The micro-processor is a miracle. But most miracles don't have a deadline. This is a case where we have to get a miracle in a pretty tight timeline. We need to get to zero emissions by 2050.[13]

What might that miracle look like? Gates short-listed the candidates. Two of these would dramatically lower the cost of electricity from solar energy: a breakthrough innovation in photovoltaic cells; a dramatic cost-reduction in concentrated solar power (parabolic mirrors that reflect sunlight to heat water into steam for generating electricity). Another candidate would link wind power with energy storage to provide cheap, reliable electricity when needed, instead of just when it's windy. Another would be a safe and low-cost design for nuclear power.

For Gates, innovation is not manna from heaven; we *make* our miracles. As Gates said, "What do we need to do? We need to go for more research funding. You would be stunned at the ridiculously low levels of funding on innovative approaches." But while Gates calls for more public and private R&D, he has stepped up to the plate with his own millions, working on a new type of nuclear plant requiring no fuel enrichment, producing no radioactive spent fuel, and generating electricity at a much lower cost than current designs.

The development of a carbon-free energy source cheaper than fossil fuels would indeed be a game-changer. It would drive emissions reduction without needing an international agreement, or to change the minds of climate skeptics. As Gates said, "If you can make it economic and meet the CO_2 constraint, then you can say to the skeptics, 'at least this is saving you money and saving the planet'."

If only more wealthy people were like Bill Gates. He has assessed the great challenges facing humanity, and focused his talent and wealth on developing solutions, while using his personal influence to rally other influential people, educating the public and pressuring governments. In a world where so few influential people seem to care, he tries to make a difference, and he does.

But his focus on innovation returns us to the question of the technical and economic feasibility of our deep decarbonization options. Do we need a carbon-free energy source that is cheaper than fossil fuels? And how big should be our innovation effort?

In an influential 2010 article in *Foreign Policy*, Ted Nordhaus and Michael Shellenberger of the Breakthrough Institute in California argued that, "Solving global warming's technology challenges will require not a single Apollo Program or Manhattan Project, but many." This is required because, "fossil fuels are remarkable sources of energy – cheap, energy dense, and widely available – [that] will not be easily displaced by present-day renewable energy technologies."[14]

Nordhaus and Shellenberger argue that without the kind of massive public commitment to research that occurred under the 1960s Apollo Program to put a man on the moon in just eight years and the 1940s Manhattan Project to build the first nuclear bomb in just three years, policies to price or regulate carbon pollution will not succeed in shifting us to a deep decarbonization path. A massive public R&D effort is essential to addressing the climate threat.

This position of Nordhaus and Shellenberger might be motivational for some people. But it's probably depressing for others like me. Most of us recognize that the climate threat thus far lacks the motivational attributes of the nuclear bomb race against fascist Nazi Germany and the space race against the communist Soviet Union. In World War II, Nazi Germany was an immediate global threat (like an asteroid coming straight at us), as it conquered Europe and invaded Africa and the Soviet Union. Given that many of the world's leading nuclear physicists were still in Germany, the Allies feared it would quickly develop a nuclear bomb. So President Franklin Roosevelt launched the Manhattan Project to build one first. With strong public support for the war, the US government was able to incur massive debt and impose rationing as it marshaled people and resources to defeat Nazi Germany. The top-secret Manhattan Project was quietly funded in this context.

The Apollo Space Program had similar motives. With the US and Soviet Union locked in the Cold War, each threatening the other with nuclear annihilation, the Soviets launched the first rockets into space, shocking America and its NATO allies. Fearing the Soviet Union would achieve nuclear supremacy through its mastery of outer space, President John F. Kennedy launched the Apollo Program – using the moon-shot as a symbol to rally public support for the space race, and its thinly veiled implications for the arms race.

In both cases, a massive public R&D effort was motivated by an immediate, acknowledged national threat. Both Japan and Germany declared war on the US, leaving it no option but to fight a war in which survival required being first to develop a nuclear bomb. The threat was national, and the solution was national. In this context, a public-financed R&D effort to make the nuclear bomb was unquestioned by the country's political leaders. Likewise with the space race. The Soviet Union's suddenly demonstrated lead in rocketry science during the Cold War presented the US with the threat of nuclear annihilation from a missile attack. The threat was national, and the solution was national. The US could act alone in using the moon landing as the symbolic goal for its massive R&D effort in the space race.

The climate change threat is different. By its own actions, the US government cannot win the climate-energy challenge. It needs other countries to help. It can develop cheaper batteries to operate with solar and wind in electricity generation or with electric vehicles in transportation. But Chinese or Indians or Indonesians or Pakistanis might still opt for coal-fired power and gasoline vehicles, as these will remain – in the absence of global pricing or regulatory policies – low-cost energy options, ones whose costs will keep falling as modest innovations free-up more fossil fuel resources.

Fortunately, we don't need a massive R&D program to decarbonize the global energy system. We already have the technologies we need. As we implement the key decarbonization policies I described in Chapter 6, modest innovations will make these options even better. Wood has been used for centuries, hydropower and geothermal for a century, and modern forms of biofuels, wind, and solar for decades. Even electric and biofuel vehicles have been around for decades, as have nuclear power and carbon capture and storage, should we also rely on these.

All of these options provide energy with negligible carbon emissions. All are commercially available today. All play an important role in part of the energy system in at least one jurisdiction. All can be more widely disseminated at moderate cost in virtually all jurisdictions. And while each of these technologies would certainly benefit from more R&D, their widespread deployment doesn't need breakthrough innovation. What they absolutely require, to overcome the high energy quality, widespread availability, and incumbent position of fossil fuels, is the adoption of compulsory policies that either price or regulate GHG emissions or the technologies that cause them.

Such policies have two important effects. First, as noted, they drive the market dissemination of commercially available technologies that would otherwise not occur. If fossil fuels are cheaper – and they usually are – low-emission technologies capture niche markets at best, even though they could play a much larger role if market prices were corrected by a rising carbon price, or if GHG-emitting technologies like coal power plants and gasoline cars were phased out by flex-regs of increasing stringency.

Second, as regulations and carbon pricing cause the wider deployment of these technologies, they also stimulate private R&D, as manufacturers compete with each other to capture market share by finding design efficiencies and innovating small adjustments to technologies that make them more attractive to customers. While public R&D is important when a major technological breakthrough is needed, private R&D tends to be narrowly targeted and more effective once a specific technology is disseminating in a competitive market.

Today, private corporations are putting their R&D money into improving photovoltaic cells, wind turbines, electric vehicles, batteries, and biofuels because these low-GHG options are already established in the market. Government R&D has certainly also played a role in reducing their costs through innovation. But the California vehicle flex-regs were instrumental in stimulating private R&D leading to hybrid, plug-in hybrid, electric, and hydrogen vehicles, along with complementary battery and fuel cell innovations. And the US state renewable electricity flex-regs, along with subsidy and regulatory policies in the US and other countries (tax rebates, feed-in tariffs), played a role in the falling costs of wind and solar, and could do more if their stringency were tightened.

The key point is that a massive public R&D effort on the scale of the Manhattan Project or the Apollo Program is not necessary for rapid decarbonization. Opponents of decarbonization are happy when climate-concerned activists and sincere politicians assume that massive public R&D is essential, as this myth sustains our procrastination on the climate-energy challenge.

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The following examples illustrate cases where government policies caused rapid energy system change and GHG reduction, while relying on commercially available technologies. Although the prime motive wasn't always GHG reduction, that doesn't matter. What matters is that the GHG reduction happened quickly, without waiting for a massive government R&D effort to produce a game-changing innovation. But compulsory policies or direct government action were essential.

From 1950 to 1980, France's CO_2 emissions from electricity generation grew in step with its electricity output. While the country had some hydropower facilities, it mostly produced electricity from coal or oil. Then, in response to the oil crisis of the 1970s, the French government decided to quickly switch its electricity system to nuclear power. Its motives included energy security, but especially a strategic bet that it could become a global leader and major exporter of nuclear power technology.

Figure 11.2 tracks the implications of this policy for CO_2 emissions. (For ease of comparison, I set both electricity generation and CO_2 emissions from electricity generation at 100 in 1975.) Over the period 1980 to 1990, electricity generation grew dramatically as France increased domestic consumption in buildings and industry, while increasing exports to its European neighbors. At the same time, CO_2 emissions from electricity generation fell 80%, thanks to the sequential construction of a series of near-identical nuclear plants.

The French government achieved this rapid energy substitution by directing its state-owned corporation, *Électricité de France*, to switch to nuclear power. Had this been a private utility, the government would have had to mandate the energy substitution. Although the government and the utility funded R&D to help this development, each nuclear plant was similar to the previous, a technology that was well established by the late 1970s.

The French development of nuclear power has a great deal of complexity that I am glossing over. Yes, electricity was a monopoly market.

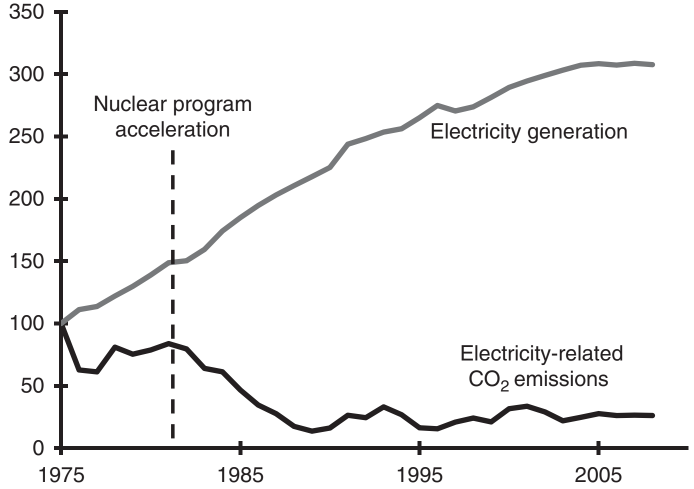

Figure 11.2 France electricity and CO_2 emissions

Yes, the government subsidized the nuclear industry by providing low-interest public loans, assuming all safety-related risks, and taking responsibility for recovering and reprocessing radioactive wastes and spent fuel. But these factors do not detract from the critical point that within just two decades, the French government reduced GHG emissions in its electricity sector by 80% through adoption of existing commercial technology.

My second example is the development of biofuels in Brazil. From 1960 to 1975, Brazil's CO_2 emissions from vehicles increased in step with the growth of vehicle stocks, as in all other countries. But the Brazilian government responded to the 1970s oil crisis by promoting domestic production of ethanol from sugarcane to reduce its oil imports. Figure 11.3 shows that, over the next three decades, vehicle-related CO_2 emissions climbed at less than half the rate of vehicle stocks. (Again, I have converted the values to equal 100 in the same year – 1971.) Today, about 50% of the fuel used by personal vehicles is from ethanol, meaning Brazil's vehicles produce half the fossil fuel-related CO_2 emissions of a country with a similar-sized fleet.

The government achieved this transition using fuel and vehicle mandates, alongside fuel taxes and some financial support for the ethanol industry, all without a major R&D effort and major innovation. (Vehicle

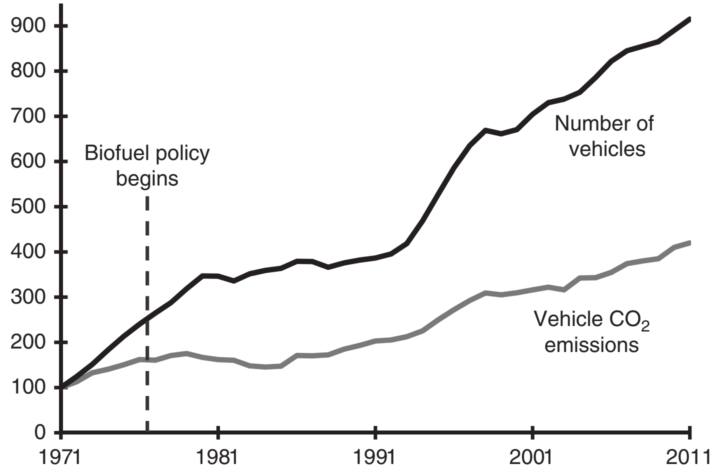

Figure 11.3 Brazil vehicles and CO_2 emissions

manufacturers have known how to run vehicles on biofuels since the introduction of the automobile.) This transition required the conversion of less than 1% of Brazilian arable land with ethanol as a co-product of sugar production for export. As noted in the *Global Energy Assessment*, the Brazilian example provides a model of rapid GHG reduction in transportation for the many tropical and sub-tropical countries with potential to produce sugarcane.[15]

My third example is the phase-out of coal-fired power in the Canadian province of Ontario in the decade 2004–2014. In 2003, coal plants met 25% of Ontario's electricity demand. But over the next decade, the 7,500 megawatts of coal-fired power were replaced by biomass used in a former coal plant, increased output from the province's nuclear plants, expanded small-scale renewables, new natural gas plants, and increased imports of hydropower from the province of Quebec.

The prime motivation for the coal plant phase-out was local air quality. Nitrous oxide emissions from the Ontario electricity sector fell 85% and sulfur dioxide emissions 99%. But GHG emission reduction was also an important objective. Electricity-sector CO_2 emissions fell 85% in just one decade, as Figure 11.4 shows.

This transformation was not costless. Electricity rates increased by about 15% during this period, which created problems for elected

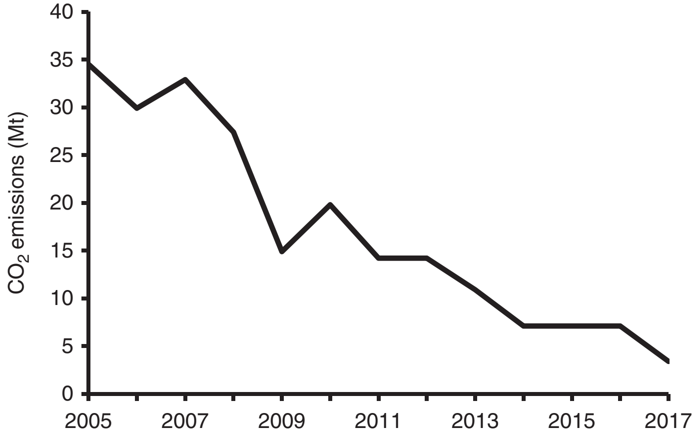

Figure 11.4 Ontario electricity emissions

officials. But some of the price increases were recognized by voters as attributable to the inefficient procurement policy (feed-in tariffs) that paid much more than necessary for solar and wind power and the relatively high management costs of the publicly owned corporation. Again, this significant transformation and rapid GHG reduction happened without waiting for a massive R&D effort to produce a major innovation, nor did it cause astronomical energy prices that are often given as the reason to delay deep decarbonization.

My fourth example is the rapid phase-out of fossil fuel use to heat Swedish buildings in the period 1985 to 2000. Prior to the 1980s, Swedish buildings were mostly heated by oil. About half of the heat was distributed in urban areas by district heating: a network of underground pipes delivering hot water from centrally located boilers, some of which cogenerate electricity. The oil crisis of the 1970s triggered a brief switch to coal by many district heat facilities, but by the late 1980s government policy focused on GHG emissions. During the next decade, district heating boilers switched to a diversity of zero-GHG energy sources, including biomass, municipal solid waste, industrial waste heat, electric boilers, electric heat pumps, and geothermal. At the same time, smaller suburban and rural buildings not connected to district heating switched from oil to electricity and biomass. The net effect was an 85% reduction in GHG emissions from Swedish buildings in just 15 years.[16]

The climate-energy challenge was the prime motive for this rapid reduction of GHG emissions in the buildings sector. The government achieved its goal with a combination of new directives to publicly owned electric and district heat utilities, tighter regulations on building efficiency, and higher fossil fuel prices with the introduction of a carbon tax in 1991.[17] The buildings fuel switch was made easier by the fact that Sweden has no fossil fuels itself, but this reality hadn't stopped it previously from importing coal, oil, and some natural gas to heat buildings. The decision to phase out fossil fuels led to slightly higher heating costs, but there was no major innovation, as the fuel switch was achieved with commercially available technologies.

My fifth example is the rapid shift to electric vehicles in Norway since 2012. Although an oil producer, Norway's domestic energy consumption produces little GHGs. Its electricity system is dominated by hydropower, and this electricity is used intensively in buildings and industry. But, as in other countries, personal vehicles mostly use gasoline and diesel. In 2001, however, Norway exempted zero-emission vehicles from its hefty car purchase tax, which can be as high as $20,000, and gradually introduced a suite of other policies including lower road taxes and parking fees, a publicly funded network of vehicle recharging stations, and increases to its carbon tax.[18] From only a small percentage of vehicle sales as recently as 2013, electric and plug-in electric vehicles grew exponentially to 22% of sales in 2015 and 50% in 2018. The government has now committed to 100% of sales by 2025 at the latest.

As I mentioned earlier, the California flex-regs and other policies played a key role in the early development of low- and zero-emission vehicles. Certainly, there was also substantial government-funded R&D. But the regulatory requirements also motivated significant private R&D, such as research by manufacturers like Toyota to develop electric motors and regenerative braking (the Prius) and by Tesla to develop long-range batteries. Of course, one should not attribute the innovations of Tesla solely to government policy. Like Bill Gates, Elon Musk is a visionary who saw where the world needed to go and figured out a winning strategy on that path, that being the development of a luxury, status vehicle to entice high-income purchasers as early adopters. In Norway, compulsory policies did the rest, proving to the world that transportation sector transformation can happen in a decade if we elect sincere governments.

These five examples illustrate that we can change components of our energy systems to rapidly reduce GHG emissions if we have the political will. While the climate-energy challenge was not the prime motivator in the case of Brazilian vehicles and the French and Ontario electricity sectors, it was with Swedish buildings and Norwegian vehicles.

In all cases, government caused the rapid change by applying the compulsory policies I described in Chapter 6 (and sometimes issuing directives to state-owned corporations). These drove the transition from fossil fuel-using technologies to commercially available low-GHG technologies.

In all cases, the policies had an upward effect on the cost of energy services (electricity, heating, vehicle mobility). Had many countries been acting simultaneously in a global effort to rapidly reduce GHG emissions, the prices of coal and oil would have fallen substantially, which is why the pricing of carbon pollution or the regulation of technologies and energy are an essential element of deep decarbonization.

In all cases, the transformation happened without massive public R&D funding on the scale of the Manhattan Project or Apollo Program. While those opposed to quick action on the climate-energy challenge happily repeat the argument that success is impossible without a massive R&D program, the reality is otherwise. The adoption of compulsory policies signals to industry the seriousness of the government's intent, rewarding those firms that invest in R&D to improve existing technologies, and perhaps innovate new ones. Innovation is gradual, driven by emerging challenges as commercial low-emission technologies and energy forms penetrate the market.

As summarized in the text box, the claim that renewables are now cheaper than fossil fuels to provide energy services is inaccurate and potentially counterproductive. Yes, the costs of some renewables have fallen substantially, meaning that deep decarbonization will not greatly increase the cost of energy services. But because the price of fossil fuels will fall in step with GHG reduction, regulations or carbon pricing are essential. Renewables advocates need to ensure that their enthusiasm does not inadvertently slow the rate of deep decarbonization by providing politicians with an excuse to further delay the essential compulsory policies.

Renewable forms of energy can play the lead role in deep decarbonization because they are plentiful and their costs are falling, as are the costs of energy storage.

The lowest cost approach to decarbonization would allow for other low-emission and negative emissions options depending on the jurisdiction – nuclear power, fossil fuels with carbon capture and storage, bioenergy with carbon capture and storage, and direct air capture.

While ongoing cost-reducing innovations with renewables are desirable, they are not an essential pre-condition for decarbonization, as case studies of past, rapid energy transitions have shown.

Regulations and/or carbon pricing are essential for deep decarbonization.

1. It ensures expansion of renewables, which in turn fosters cost-reducing innovations.
2. It ensures that falling fossil fuel prices do not hinder the growth of renewables.

Wishful thinking claims that renewables have won and now outcompete fossil fuels undermine the rationale for regulations and/or carbon pricing, yet these are essential and must be applied with rising stringency.